Jet Propulsion Laboratory
California Institute of Technology

Overview of the ASPIRE Project's SR01 Supersonic Flight Test

IEEE Aerospace Conference

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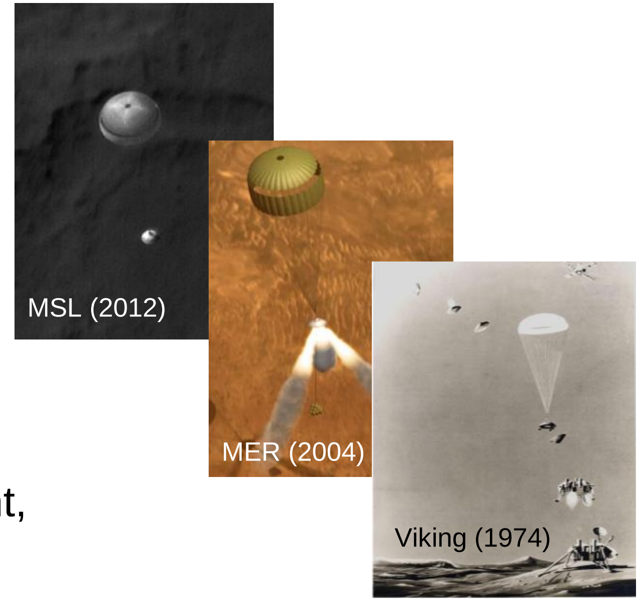
ASPIRE

The ASPIRE Project

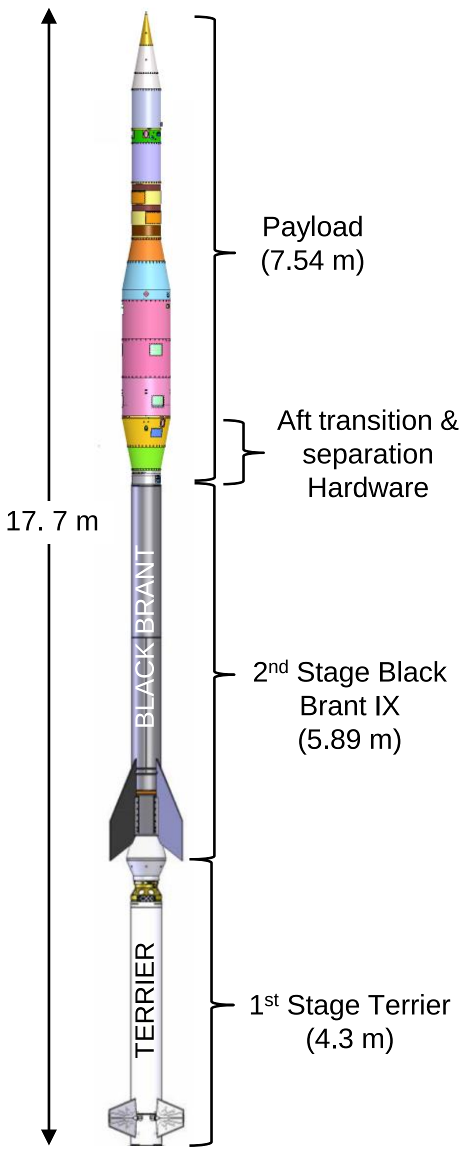
- Disk-Gap-Band (DGB) parachute: developed in the 60s & 70s for Viking & successfully used in 5 Mars missions.
- **A**dvanced **S**upersonic **P**arachute **I**nflation **R**esearch **E**xperiments Project Objectives:
  - Develop testing capability for supersonic parachutes at Mars-relevant conditions.
  - Deliver 21.5m parachutes to low-density, supersonic conditions on a sounding rocket test platform
  - Acquire data sufficient to characterize flight environment, loads, and performance



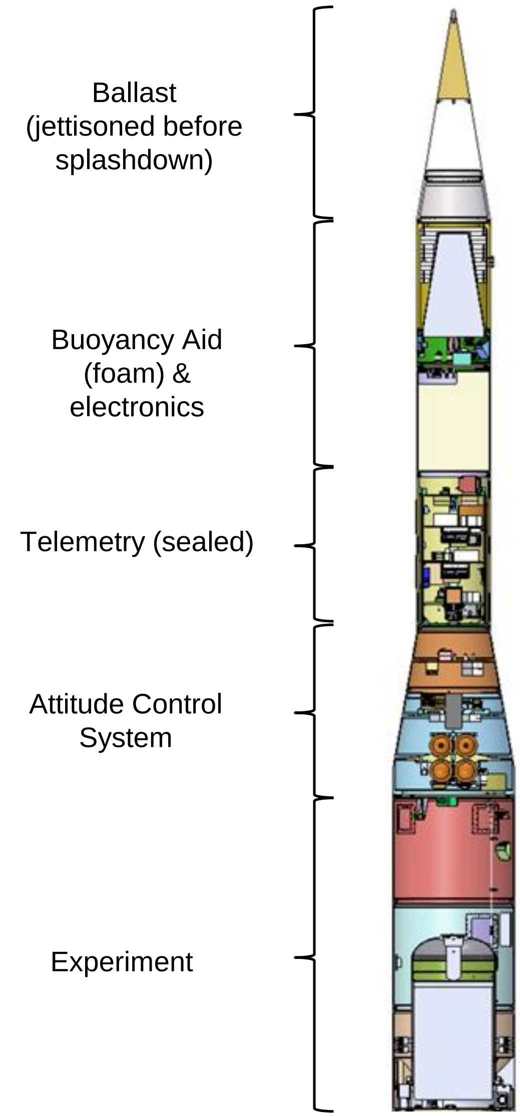
- Initial flights focused on testing candidate designs for Mars2020:
  - Built-to-print Mars Science Laboratory (MSL) DGB
  - Strengthened version of MSL DGB with stronger broadcloth

	Parachute	Load	Purpose	Test Date
SR01	MSL built-to-print	35 klbf (MSL @ Mars)	Test architecture shakeout. Ensure test approach doesn't introduce new parameters.	Oct 4th., 2017
SR02	Strengthened	47 klbf	Incremental strength test of new design.	Mar. 20th, 2018
SR03	Strengthened	70 klbf	Strength test of new design	May 30th, 2018

Test Architecture

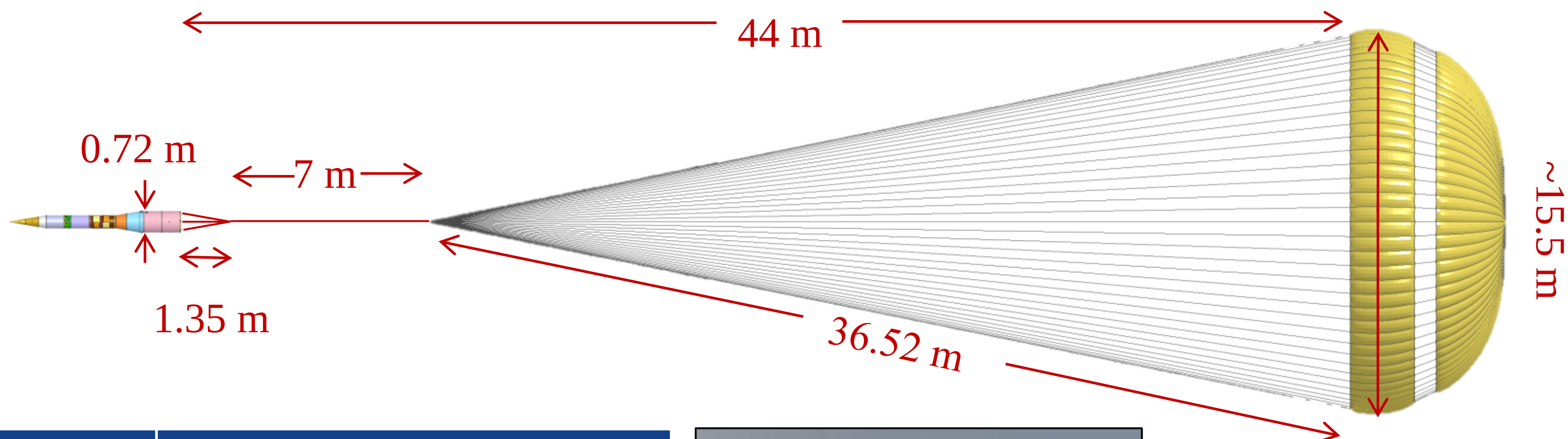


- Rail-launched Terrier Black Brant
- Spin-stabilized at 4 Hz
- Yo-yo de-spin after 2nd stage burnout
- Mortar-deployed full-scale DGB
- Cold gas ACS active from payload separation to before mortar fire
- Recovery aids:
  - Foam provides buoyancy
  - Nosecone ballast (for additional mass & aerodynamic stability) is jettisoned before splashdown
- Payload mass:
  - Launch: 1268 kg
  - Post-separation: 1157 kg
  - Splashdown: 495 kg



Test Article

SR01 tested a built-to-print MSL DGB parachute:



	As-built-dimensions
D_0	21.31 m
Geometric porosity	12.8%
No. of gores	80
SL line material	2100 lb Technora
Band fabric	PIA-C-7020 Type I Nylon
Disk fabric	PIA-C-7020 Type I Nylon (skirt) Polyester 8860 (crown)
Radials	2100 lb Technora
Mass	49.8 kg
Fabric permeability	100 cfm

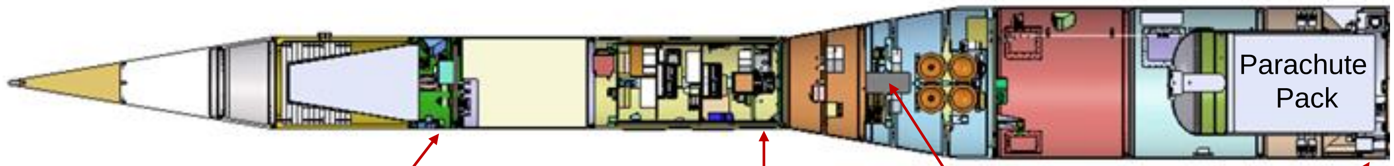
For additional details:

Overview of the Mars 2020 Risk Reduction Activity

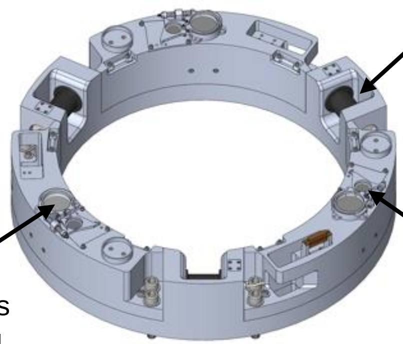
Tanner, Clark, & Chen

(11:25am this session)

Instrumentation

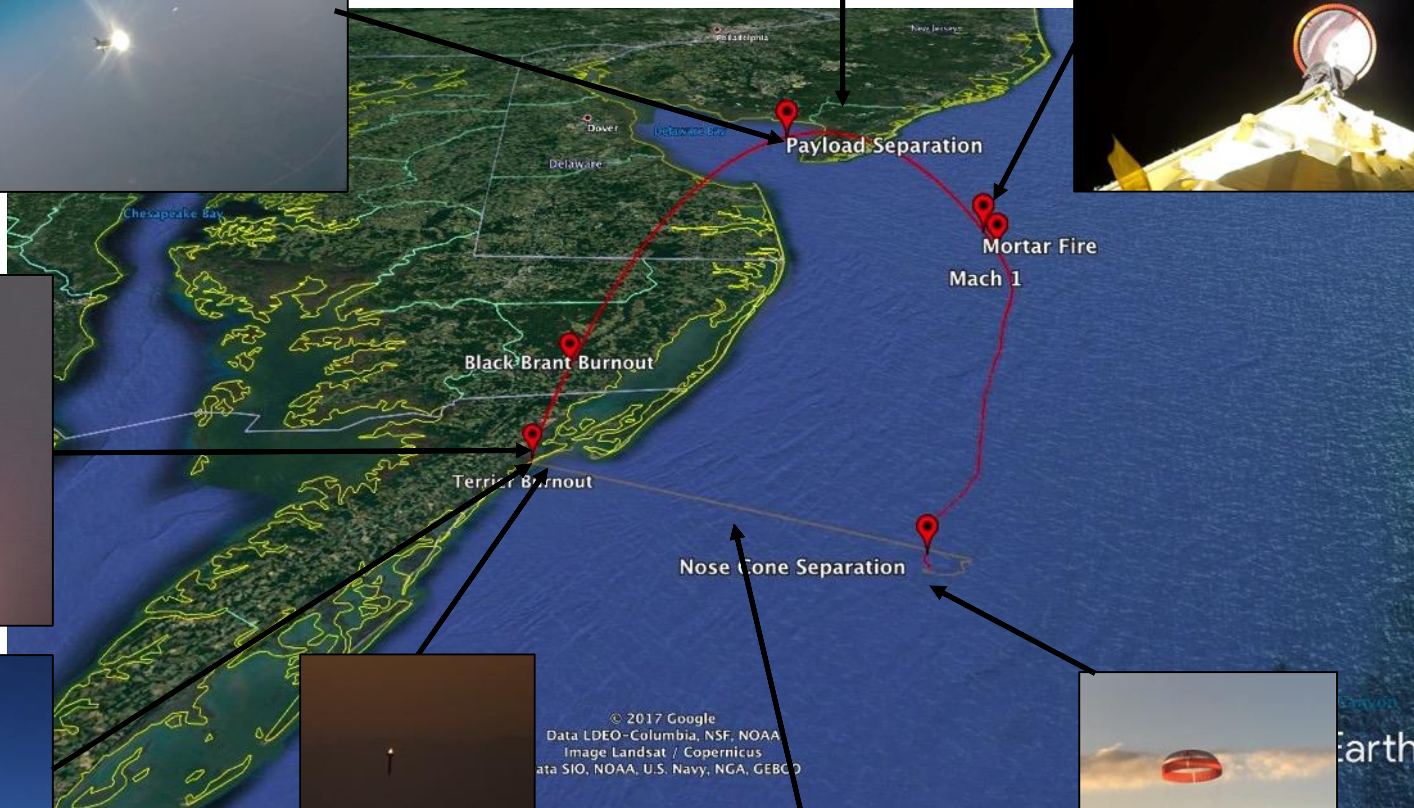


- GLN-MAC IMU: Gimbaled LN-200 w/Miniature Airborne Computer
  - LN200 measures rates & accels at 400 Hz
  - Resolver measures gimbal angle at 400 Hz
  - Navigated solution (w/blended GPS) at 100 Hz
  - Mortar fire triggered on computed wind-relative dynamic pressure
- Javad TR-G2 GPS
  - Tracked 10/11 satellites throughout flight
- Radar C-band tracking @ 50 Hz
- Custom Strainsert triple bridle load pins:
  - Rated to 90 klbf/calibrated to 25 klbf
- 3x IDT OS10 HS cameras
  - 1000 fps over 5 seconds
  - Synchronized for stereo reconstruction
  - 1x failed to trigger



SR01 Flight Sequence

Apogee
L+119 s (51 km)

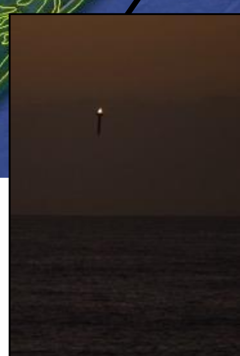


Mortar Fire
L+161 s
Alt: 42 km
q_∞: 453 Pa
Mach: 1.77

Peak Load
MF +1.47 s
q_∞: 500 Pa
Mach: 1.77

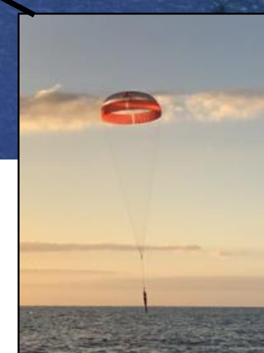
Nosecone sep.
L + ~26 min
Alt: 3 km

Launch 6:45 EDT.
Wallops Island, VA



1st stage burnout
L+6.2 s (1 km)

Range
55 km



Splashdown
L + ~24 min

SR01 Video

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Test Conditions

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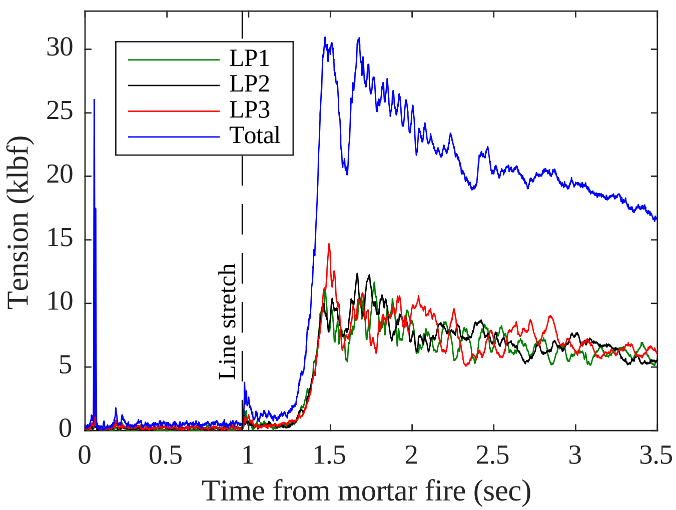
Event	Time from launch (sec)	Mach number	Dynamic pressure (Pa)	Wind-relative velocity (m/s)	Geodetic altitude (km)	Flight path angle (deg)
Launch	0	0.01	8.07	3.61	-0.02	36.2
Spin Up	1.18	0.21	3070.53	70.53	0.02	79.8
Terrier Burnout	6.23	0.8	41109	273.26	1.06	76.3
Brant Ignition	8.02	0.74	33482	253.3	1.52	74.7
Brant Burnout	34.27	3.4	89582	979.29	15.97	64.1
Despin Begin	100.09	1.32	102.08	423.54	49.27	25.4
Payload Separation	104.03	1.27 (1.2)	87.15 (86.1)	407.8	49.92 (49.9)	20.6
Apogee	**119.04**	**1.19**	**65.74**	**379.66**	**51** (50.9)	**0**
Mortar Fire	**161.41**	**1.77** (1.74)	**452.53** (438.4)	**560.29**	**42.4**	**-46.4**
Line Stretch	**162.37**	**1.79**	**491.82**	**567.74**	**42.01**	**-47.1**
Peak Load	**162.88**	**1.77** (1.72)	**494.88** (473.0)	**560.94**	**41.8**	**-47.4**
Mach 1.0	167.02	1	188.15	314.74	40.48	-53
Nose Cone Jettison	1554	0.03	45.01	10.06	3.02	-85.2
Splashdown	2056	0.02	38.21	7.87	0.02	-41

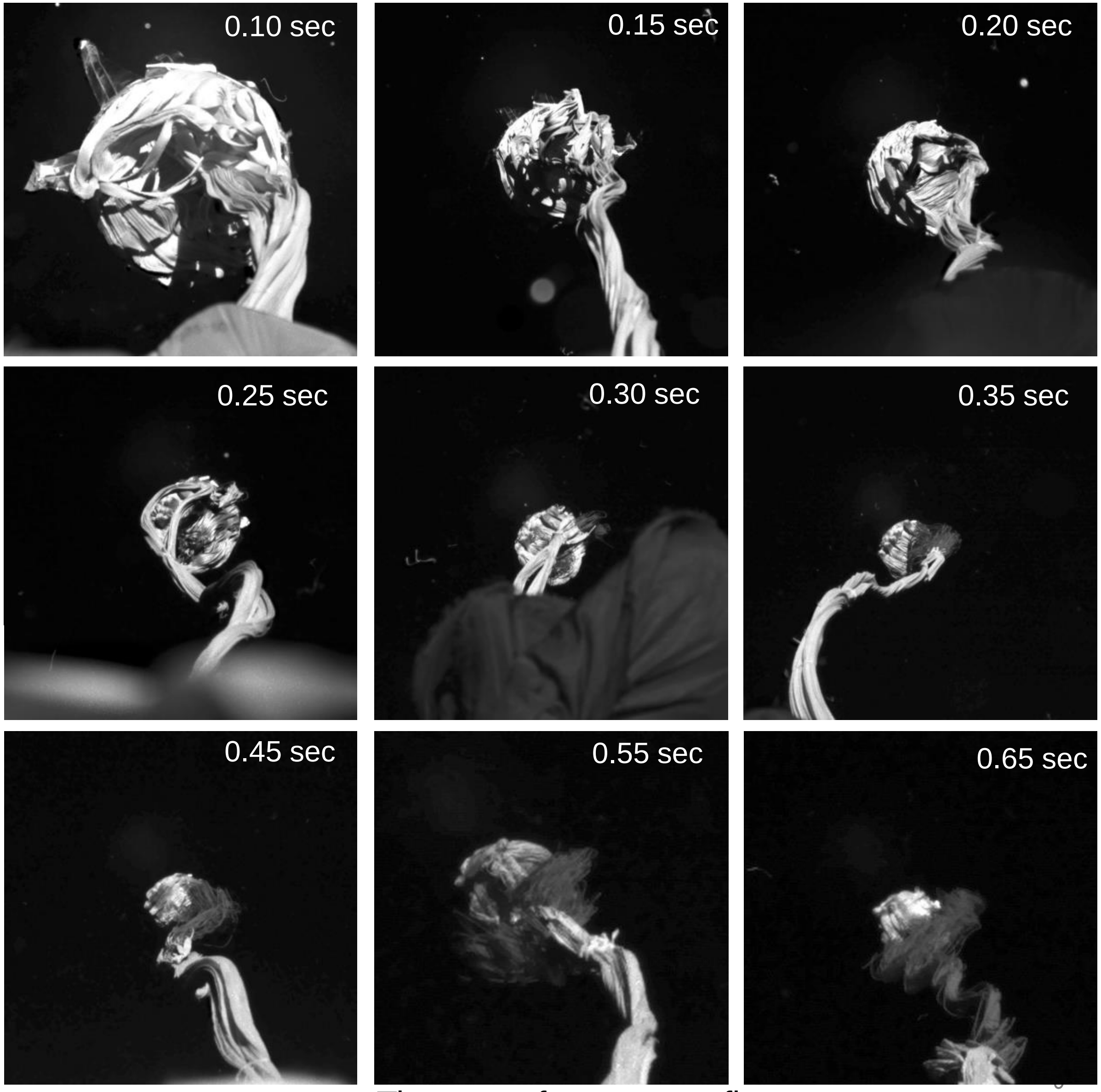
( ) Pre-flight prediction

- Target dynamic pressure at peak load: 473 Pa (MSL @ Mars)
- Corresponding target dynamic pressure at mortar fire: 438.35 Pa.
- Exceeded *q* at mortar fire by 3.2%
- Exceeded *q* at peak load by 4.6%

Parachute Deployment

- Mortar velocity:
    - 45.7 m/s effective ground velocity (ΔV applied to payload of ~2.8 m/sec)
    - 45 m/s ground testing average
- Time to Line Stretch:
    - Defined as *start* of tension rise associated w/snatch
    - 0.961 sec after mortar fire





Times are from mortar fire

Parachute Inflation

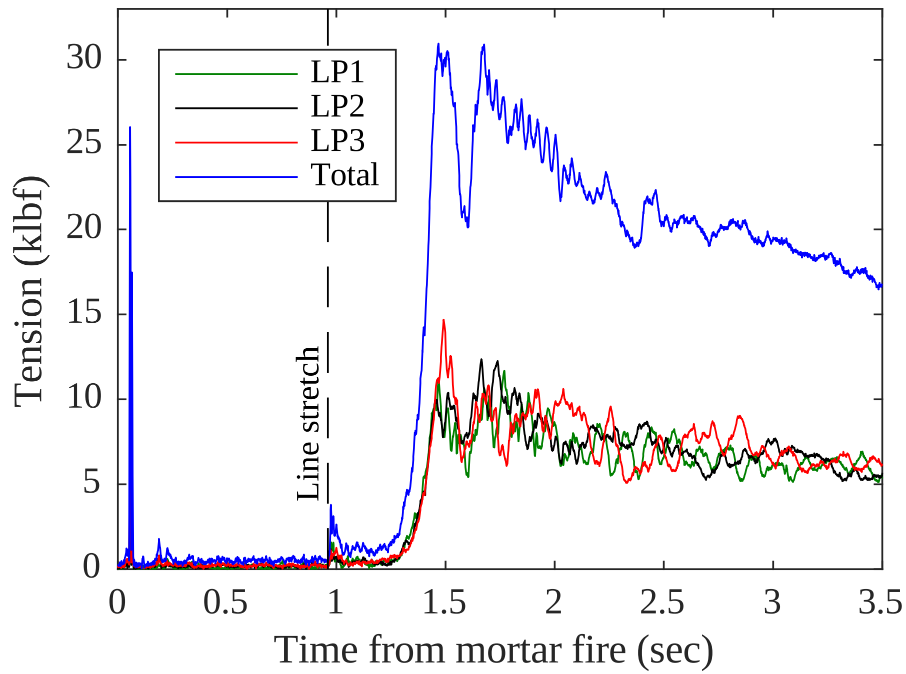
- Full inflation at q = 494.88 Pa and Mach 1.77
- Peak tension measured by bridle pins: 30.95 klbf
- Including mass north of the pins & deceleration: 32.39 klbf

- Considering the conservation of momentum inside a control volume around the inflating canopy:

$$F_{peak} = k_p(2q_\infty S_p)$$

k_p = fraction of the fluid momentum converted to parachute drag

- Can also compute k_p for 2nd peak in tension (31.63 klbf)



	k_p
1st peak	0.77
2nd peak	0.79
MSL	0.83

A Momentum-Based Method for Predicting the Peak Opening Load of Supersonic Parachutes. D. Way. **Today 4:30pm. Madison**

Parachute Aerodynamics

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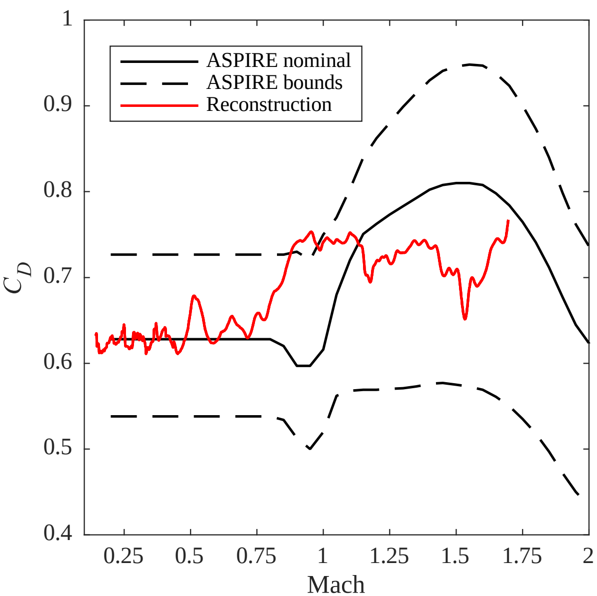
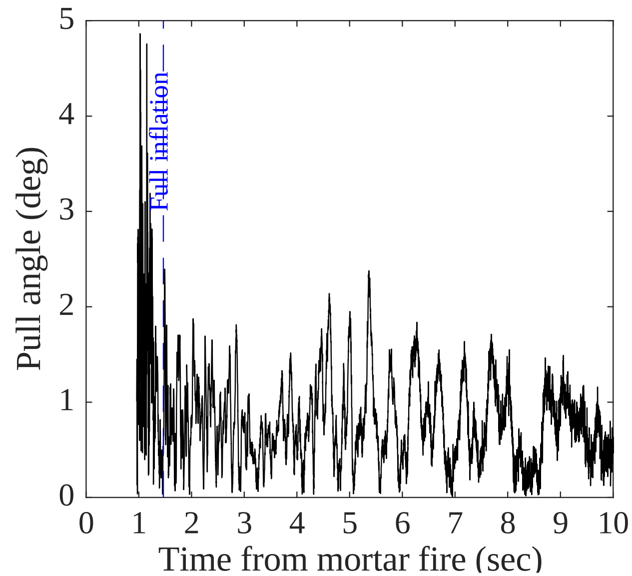
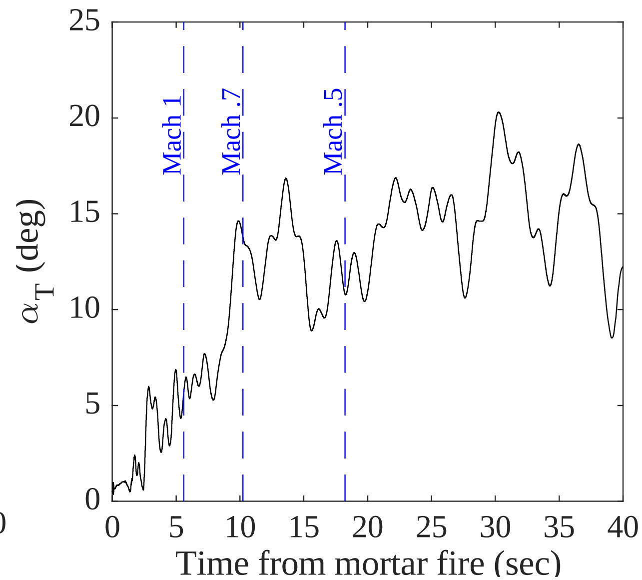
- Determined the parachute force coefficients from:
  - The loads measured by the triple bridle load pins
  - The product of mass & acceleration (after subtracting payload aero contributions)







- Good agreement with C_D model below M = 0.75 , but over-estimated C_D for M >1.15
- C_D remained constant in transonic region
- Parachute force vector “pull angle” generally remained < 2.5 deg after full inflation (w/increases due to windshear events)
- Wind-relative total angle of attack oscillated about 15 deg for the majority of the flight
- Splashdown < 0.5 nmi of prediction. Inspection revealed no significant damage

Conclusions & Future Work

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- SR01 was a success:

Criterion	
Deliver the experiment to the required test conditions	Met
Acquire, transmit, and record the required experiment data	Met
Recover the experiment section without recovery-induced damage to data	Met
Recover sufficient data to determine parachute peak load	Met
Recover the parachute assembly without recovery-induced damage	Met

- Ongoing work:
  - 3D canopy shape reconstruction from stereo videography
  - Investigate supersonic C_D: CFD with flight-like conditions & geometry
  - Static aerodynamic coefficients & parachute/payload dynamics
- SR02 launch window opens March 20:
  - Strengthened DGB canopy w/ 47 klbf target load
  - No changes other than resolved camera issue

Acknowledgements

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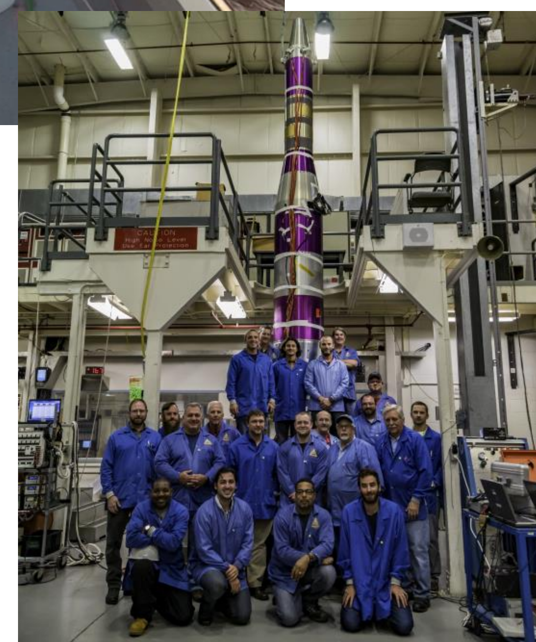
The ASPIRE team at JPL, Langley Research Center, Wallops Flight Facility & Ames Research Center



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Backup

SR01 Atmosphere

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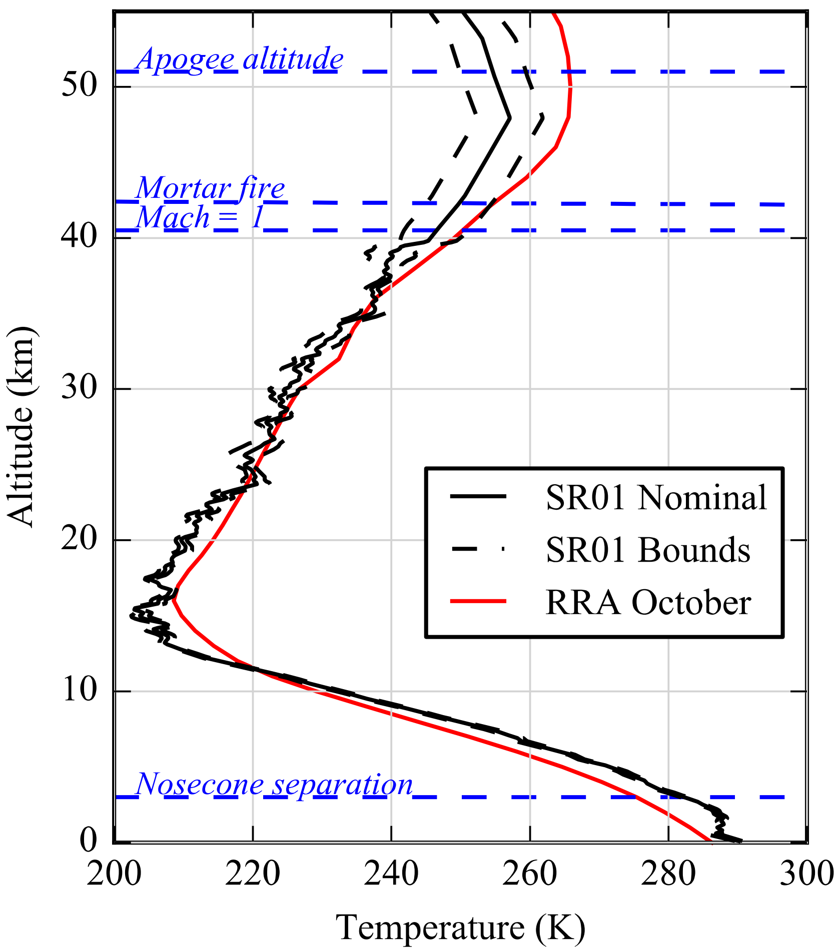
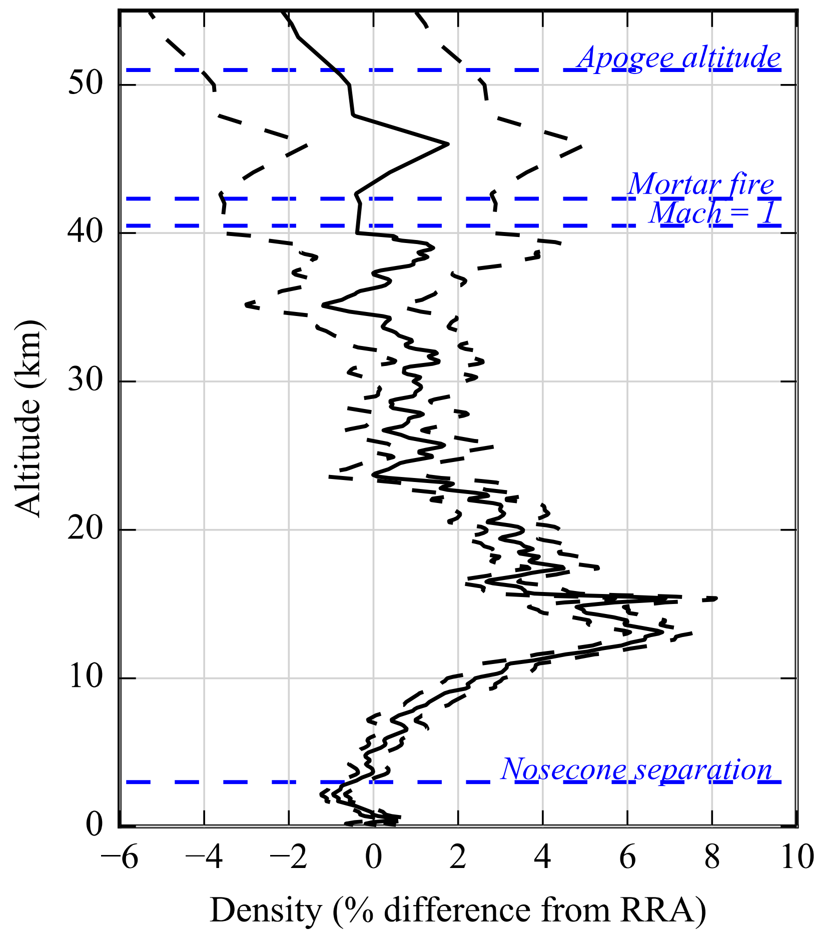
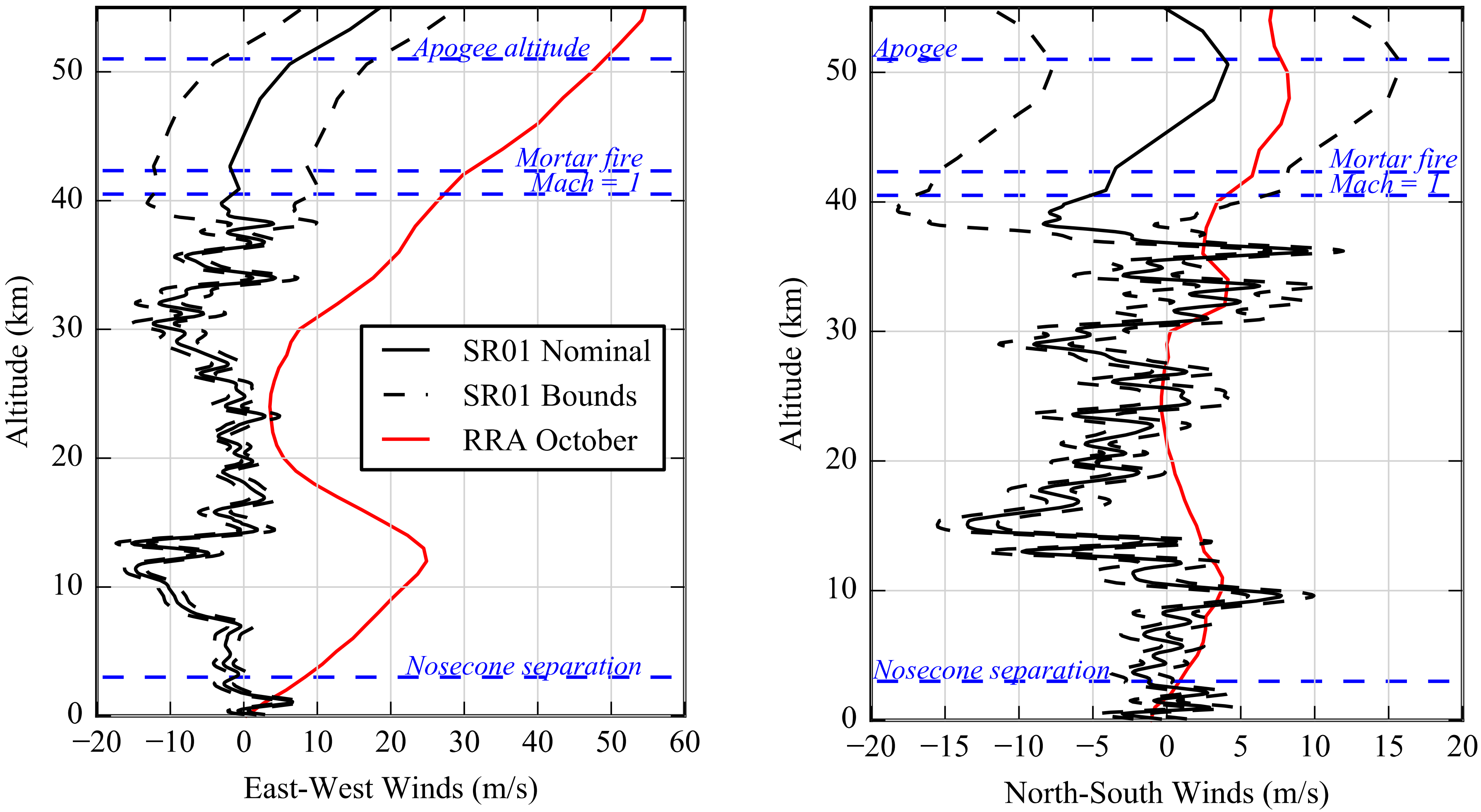
- 4x meteorological ballo0ns carrying radiosondes**:**
  - He-filled 3000g latex balloon (Totex TA3000)
  - Launched at L-3 hrs, L-2:15 hrs, L-1:45 hrs, L-1 hrs, 120 minute ascent time
  - Min. burst altitude: 35 km, Max. burst altitude: 39.9 km
  - LMS-6 radiosonde: chip thermistor, capacitive humidity sensor, GPS
- GEOS-5:
  - Real-time analysis generated by GMAO @ GSFC 75 min after launch
  - Winds, density, temperature pressure from 0 to 65 km
  - Excellent agreement w/Radiosonde mean, but does not capture small-scale variations
- Below 40 km:
  - Nominal based on L-1:45 radiosonde
  - Uncertainties based on measurement error + variation among radiosondes
- Above 40 km:
  - Nominal based on GEOS
  - Uncertainties based on max. observed difference between Radiosondes & GEOS
- L-0 atmosphere was atypical for October:
  - Almost no East-West wind
  - Slightly colder (and denser) atmosphere than expected

Atmosphere Reconstruction



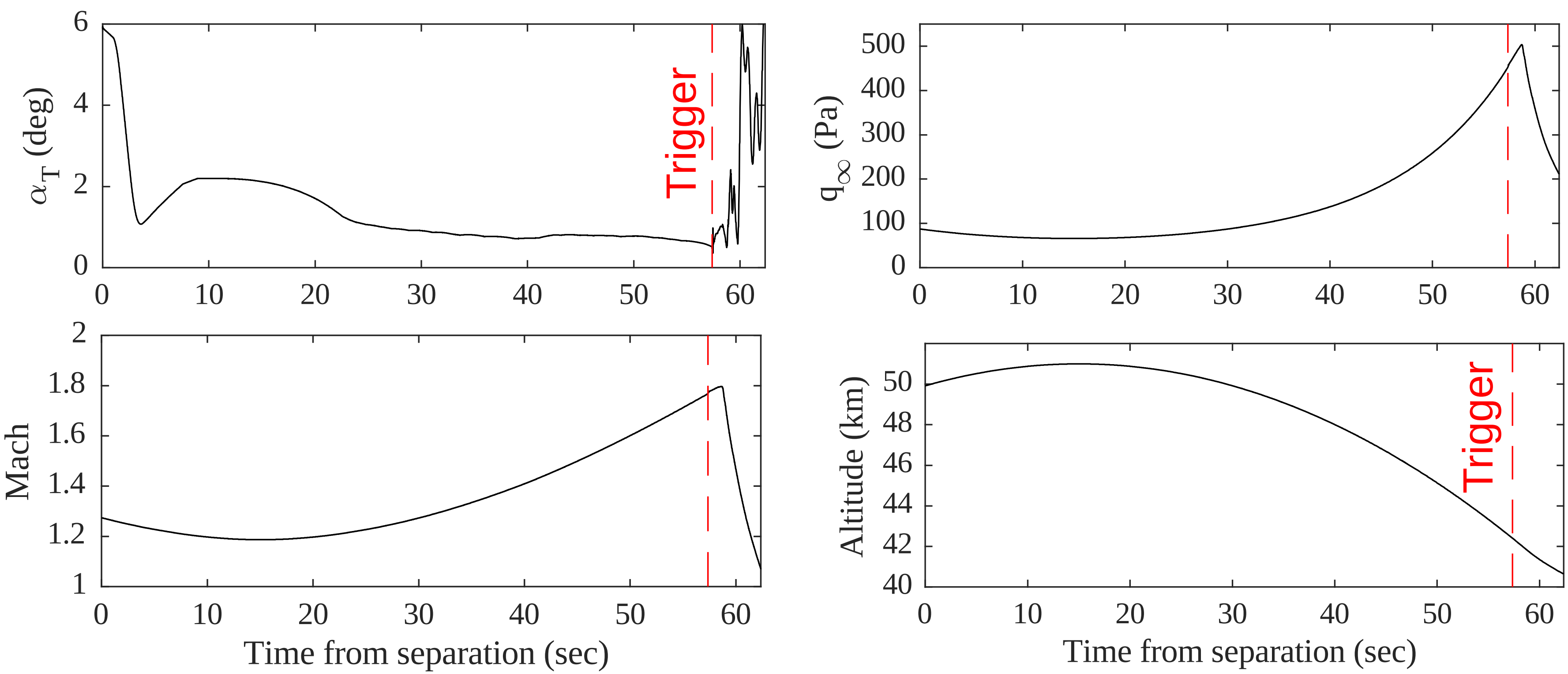


Atmosphere Reconstruction



Launch Vehicle & Payload Performance

- Payload separation at 49.9 km and 407.8 m/s
- Apogee at 51.0 km
- NIACS maintained wind-relative attitude near 0 deg & rates below 2 deg/s
- Deployment sequence triggered at q = 400.2 Pa (3.4% above target) and Mach = 1.73.
- Mortar fire occurred at q = 452.5 Pa (3.2% above prediction) and Mach 1.77.



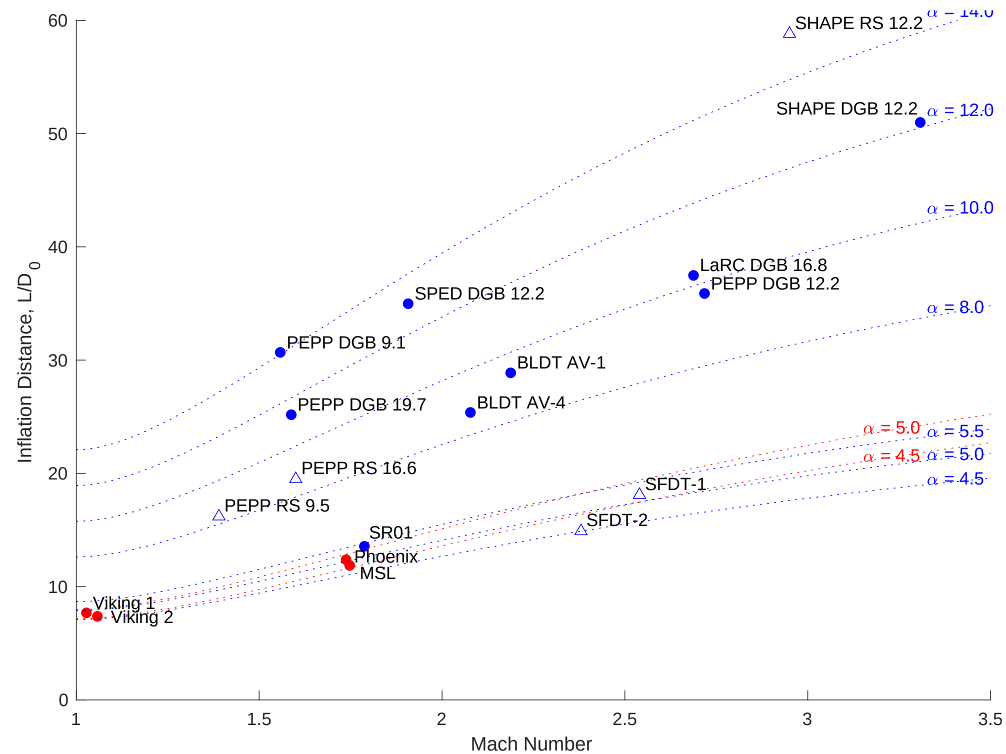
Parachute Inflation Distance

Time to full inflation modeled on an *inflation distance* approach: distance required to ingest the volume of air required for inflation

$$\frac{L_{inf}}{D_0} = \alpha\left(\frac{\rho_c}{\rho_\infty}\right)$$

$\left(\frac{\rho_c}{\rho_\infty}\right)$ = ratio of density in canopy to freestream density

	α
SR01	4.78
MSL	4.6
Phoenix	4.8



Payload Attitude During Chute Phase

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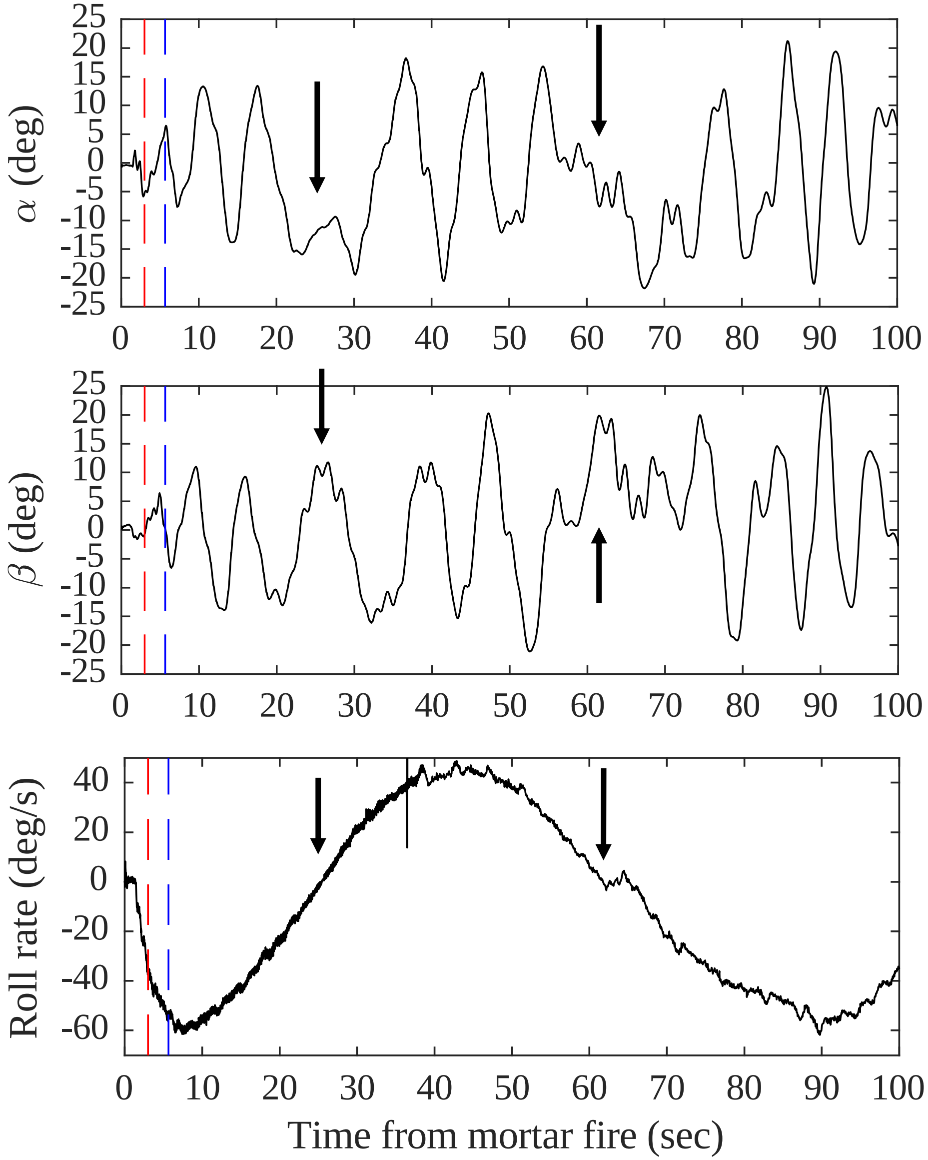
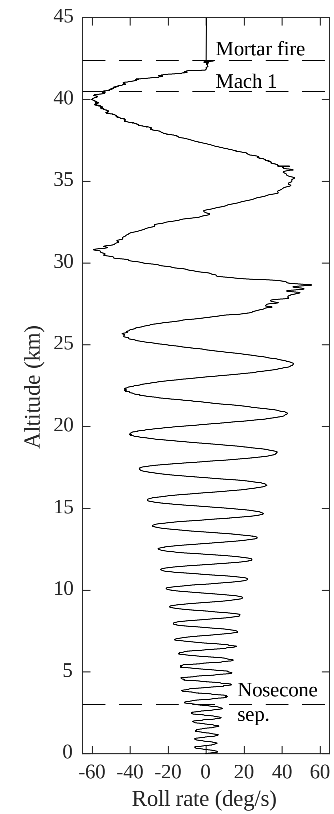


- Payload spun about roll axis, twisting & untwisting riser
- Irregularities in α and β due to roll reversals
- Spinning motion continues throughout descent:



Mach 1.4

Mach 1.0

Parachute-Payload Dynamics

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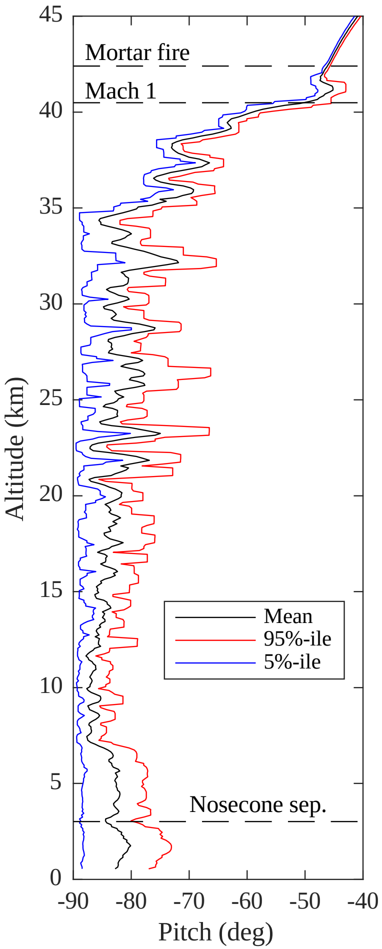
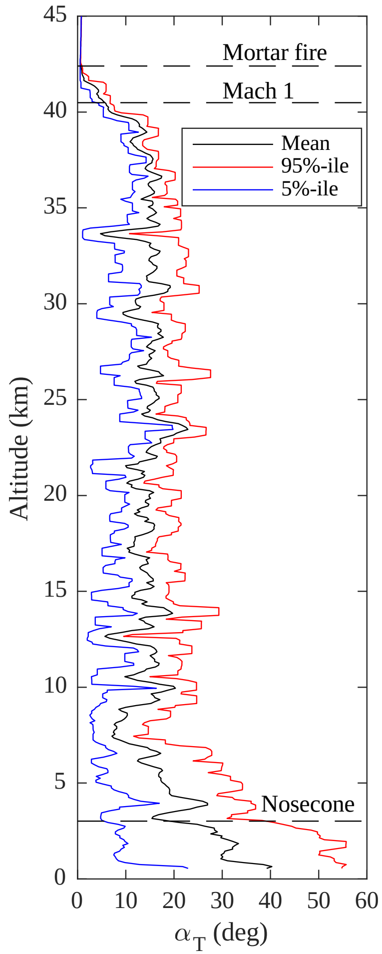
Payload attitude throughout descent

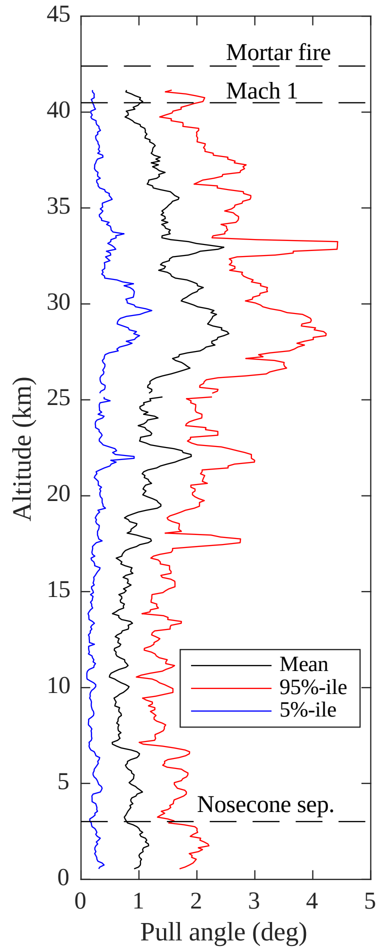
Pitch

α_T





Parachute pull angle



- Payload pitches over by ~35 km and then oscillates about vertical
- α_T increases to ~15 deg and remains constant until ~7km
- Increase in pitch and α_T below 7 km
- Pull angle remains small throughout
- System largely behaves as a rigid body

Parachute-Payload Dynamics

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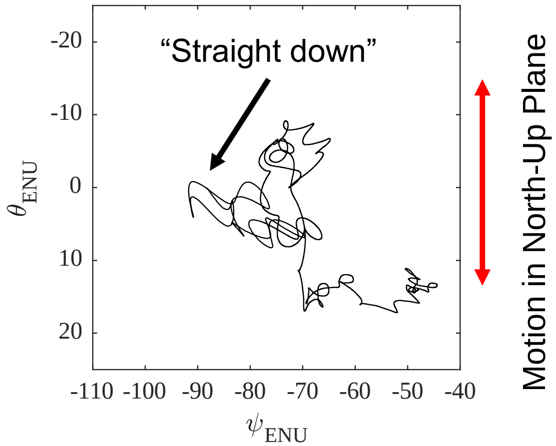
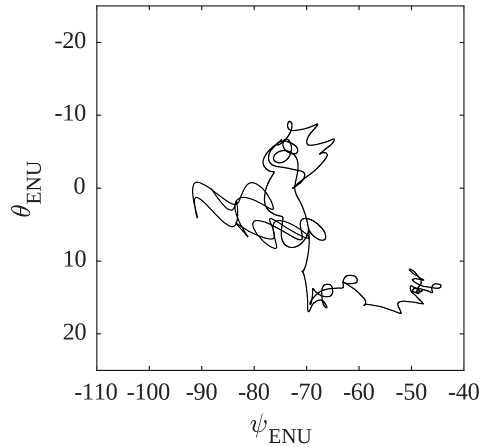
- Euler angles (pitch-yaw-roll sequence) wrt to East-North-Up frame:

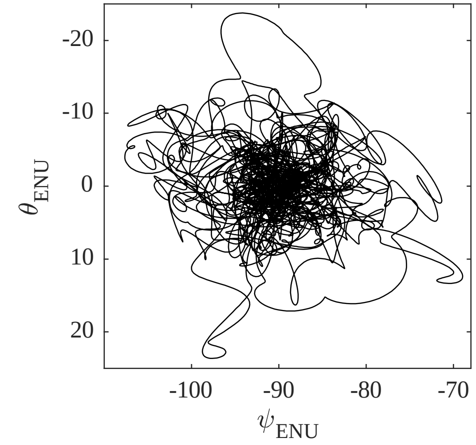


Motion in East-Up Plane

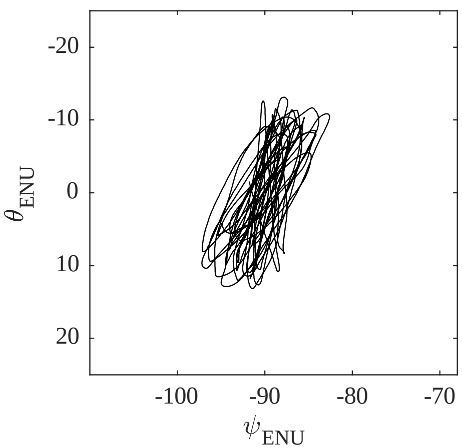
Mortar fire to 35 km:
Pitch-over motion



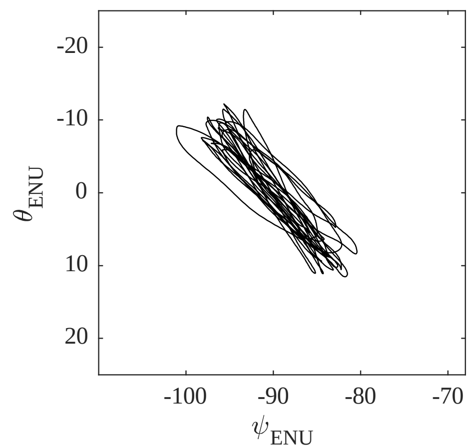
35 km to 7 km:
Chaotic motion about (-90,0)



7 km to 4.5 km:
Planar pendulum motion



4.5 km to 3 km:
Planar pendulum motion



3 km to splashdown:
Nosecone drop increases amplitude